LCA Methodology

Allocation Procedure in Multi-Output Process: An Illustration of ISO 14041

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Abstract. Allocation results for a multi-output process in a life cycle assessment study depend on the definition of the unit process which can vary with the depth of a study. The unit process may be a manufacturing site, a sub-process, or an operational unit (e.g. distillation column or reactor). There are three different approaches to define a unit process: macroscopic approach, quasi-microscopic approach, and microscopic approach. In the macroscopic approach, a unit process is the manufacturing site, while a unit process in the quasi-microscopic approach is a sub-process of the manufacturing site. An operational unit becomes the unit process in the microscopic approach.

In the quasi-microscopic and the microscopic approaches, a process can be subdivided into a joint process, a physically separated process which is physically apart from other processes, and a fully separated process. Each type can be a unit process. Therefore, the multi-output process in the quasi-microscopic and the microscopic approaches can be subdivided among two or more unit processes depending on the actual operations.

The allocation in the fully separated process can be avoided because this process fulfills one function. In the joint process and the physically separated process, which deliver two or more functions, allocation is still required.

Ammonia manufacturing, where carbon dioxide is formed as a byproduct is given to show a specific detailed example of the allocation procedure by subdivision in ISO 14041. It is shown that the quasi-microscopic and the microscopic approaches can reduce the multi-output allocation of a given chemical product. Furthermore, the quasi-microscopic and the microscopic approaches are very useful in identifying key pollution prevention issues related with one product or function.

Keywords: Allocation; ammonia; carbon dioxide; life cycle assessment; life cycle inventory analysis; macroscopic approach; microscopic approach; multi-output process; quasi-microscopic approach

1 Introduction

A multi-output manufacturing site in life cycle assessment studies is a process by which two or more products/functions are delivered. This kind of process frequently arises in chemical manufacturing. Since life cycle assessment study usually focuses on only one product/function, the responsibility of the environmental loadings associated with a multi-output process should be allocated to each product/function by a proper procedure, which is called as a multi-output allocation.

Recently, various allocation approaches for multi-input/output process are reported [1-4]. Azapagic and Clift [1] suggest that the allocation should be done by marginal changes, which reflects the partial derivatives at the point of operation. However, they state that the marginal change method is not applicable for a fixed ratio between product and byproduct like an ammonia plant where the stoichiometric ratio between ammonia and carbon dioxide is fixed. Frischknecht [2] presents the allocation approach that is a combination of economic and environmental evaluation of multi-input/out process. Ekvall [3] points out problems in Frischknecht's approach such as the discrepancy of economic value, uncertainty in quantifying environmental burdens in monetary units, and inconsistency with other information generated in LCA studies. Ekvall and Finnveden [3] propose an allocation procedure where different allocation approaches are applied depending on the importance of the effects of allocation on a decision. Huppes [4] subdivides a process into a separated sub-process, a combined sub-process, and a fully joint sub-process by using a cost allocation method in order to avoid or minimize the allocation. It is not clear how far to split a process into sub-processes or operational units.

According to ISO 14041[5], "... Wherever possible, allocation should be avoided by: 1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes ..." The multi-input/output allocation results therefore are dependent on the choice of a unit process.

From ISO 14040 [6], "The unit process in life cycle assessment is defined as a smallest portion of a product system for which data are collected when performing a life cycle assessment." The term of "a smallest portion of a product system" seems to depend on the data availability or the depth of study. Hence, which allocation procedure you select depends on the information constraints of the study and thus the results will depend on the allocation procedure.

The unit process may become a plant that manufactures a component or material used in the product system, a sub-process in a plant, or an operational unit like a distillation column or a reactor in the same plant. The conventional way to define a unit process is a macroscopic approach, where a manufacturing plant is taken as the unit process. Some allocation procedure is required for the macroscopic approach. This is one of the most common allocation strategies used in life cycle studies.

According to Huppes [4], the unit process in LCA study becomes a sub-process where the operational units in the process can be grouped into a sub-process depending on the function. This is called as a quasi-microscopic approach. Another concept is a microscopic approach where the unit process in LCA study becomes an operational unit, such as a pump. The allocation procedure in the quasi-microscopic or the microscopic approach depends on what function a unit process fulfills.

From our database of chemical LCI, about 20% of chemical manufacturing process generate byproducts of potential value. Thus, to expand the chemical life cycle field, allocation must be routinely used. The motivation of this study is to illustrate allocation approaches in the specific case of chemical manufacturing. This study also shows, for a specific detailed example, the allocation procedure by the subdivision of unit processes as described in formal, sometimes abstract terms in ISO 14041. The multi-output allocation in the ammonia manufacturing process is explored to show the difference among the allocation approaches. The ammonia manufacturing process produces carbon dioxide as well as ammonia.

2 Methodology of Case Study

2.1 Ammonia manufacturing process

Ammonia is synthesized by a catalytic reaction of hydrogen with nitrogen [7-11]. The raw material sources are however natural gas (or hydrocarbon or coal), air, and water. The process diagram for the ammonia manufacturing process is presented in **Fig. 1** where natural gas is used as a hydrogen source, with hydrogen formed by a steam reforming. Mass flow and energy requirements for this process are shown in **Table 1** (→ *p. 223*). The calculations are done with a rule-based methodology [12].

The rule-based methodology for generating an LCI is a gate-to-gate approach using accepted chemical engineering design procedures. These procedures encompass the reaction/conversion of inputs followed by the separation/purification to produce an acceptable chemical product. Rules for design are set to streamline calculations while still capturing the chemistry characteristics of creating each chemical product. For example all process equipment is set 15 m apart so as to streamline the pumping and handling calculations. These rules are a compromise between intense, resource expensive calculations leading to an improved optimized process and the practicality of establishing a large number of chemical life cycle inventories. Further details are provided in Jiménez-González et al [12].

Flue gas from the NH_3 separator B indicated by (42) in Fig. 1 is assumed to be used as a fuel within the ammonia manufacturing process because of a high concentration of methane and hydrogen. The negative energy values in Table 1 (listed as energy recovery) represent recovered energy that is used in heating steam or water within the process.

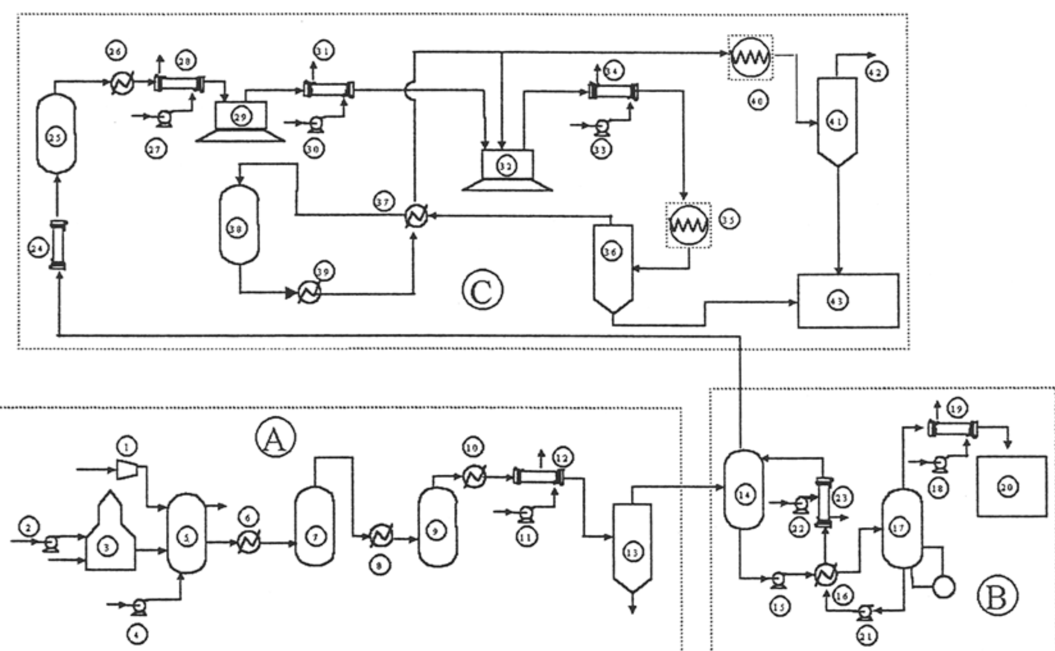

Fig. 1: Process diagram for ammonia manufacturing process. Section (A) is the synthesis gas preparation sub-process, section (B) is the carbon dioxide separation/purification sub-process, and section (C) is the ammonia synthesis sub-process.

Table 1: Energy balance in the ammonia manufacturing process [12]

No.	Equipment	Input material [kg]	Energy [MJ]	Energy recovered [MJ]	Inlet Temp. [°C]
1	Compressor for Air	Air–1108	6.99E+02	-	25
2	Pump A	Water–1200	3.46E-03	-	20
3	Primary reformer	Natural gas–447/ Water–1200	9.86E+03	-	25
4	Cooling water pump A	Cooling water–14590	3.42E-02	-	20
5	Secondary reformer	CH_4–103/ H_2–146/ CO_2–354/ CO–375/ Water–669/ N_2–850/ O_2–258	-1.27E+03	-9.50E+02	788/498
6	Heat recovery A	CH_4–9/ H_2–146/ CO_2–289/ CO–581/ Water–880/ N_2–850	-3.52E+03	-3.52E+03	974
7	High temperature shift converter	CH_4–9/ H_2–146/ CO_2–289/ CO–581/ Water–880/ N_2–850	-	-	360
8	Heat recovery B	CH_4–9/ H_2–181/ CO_2–1044/ CO–101/ Water–571/ N_2–850	-1.38E+03	-1.38E+03	486
9	Low temperature shift converter	CH_4–9/ H_2–187/ CO_2–1186/ CO–10/ Water–513/ N_2–850	-	-	243
10	Heat recovery C	CH_4–9/ H_2–187/ CO_2–1186/ CO–10/ Water–513/ N_2–850	-2.27E+03	-1.02E+03	267
11	Cooling water pump B	Cooling water–16360	4.71E-02	-	20
12	Cooler A	CH_4–9/ H_2–187/ CO_2–1186/ CO–10/ Water–513/ N_2–850	-3.37E+02	-8.41E+01	90
13	Separator A	CH_4–9/ H_2–187/ CO_2–1186/ CO–10/ Water–513/ N_2–850	-	-	40
14	CO_2 Absorber	CH_4–9/ H_2–187/ CO_2–1186/ CO–10/ N_2–850/ MEA–3046/ Water–12180	-	-	40
15	Pump B	CO_2–1179/ MEA–3046/ Water–12180	4.73E-02	-	76
16	Heat exchanger A	-	-	-	-
17	CO_2 Stripper	CO_2–1179/ MEA–3046/ Water–12180	2.38E+03	-	82
18	Cooling water pump C	Cooling water–532	1.53E-03	-	20
19	Cooler B	CO_2–1179	-5.68E+01	-1.42E+01	82
20	CO_2 Storage tanker	CO_2–1179	-	-	25
21	Pump C	MEA–3046/ Water–12180	4.39E-02	-	82
22	Cooling water pump D	Cooling water–20290	7.01E-02	-	20
23	Cooler C	MEA–3046/ Water–12180	-2.17E+03	-5.42E+02	78
24	Heater	CH_4–9/ H_2–187/ CO_2–7/ CO–10/ N_2–850	7.61E+02	-	76
25	Methanator	CH_4–9/ H_2–187/ CO_2–7/ CO–10/ N_2–850	2.86E+01	-	288
26	Heat recovery D	CH_4–17/ H_2–184/ N_2–850/ Water–9	-6.84E+02	-4.10E+02	313
27	Cooling water pump E	Cooling water–2826	8.14E-03	-	20
28	Cooler D	CH_4–17/ H_2–184/ N_2–850/ Water–9	-3.02E+02	-7.54E+01	121
29	Steam-turbine centrifugal compressor A	H_4–17/ H_2–184/ N_2–850/ Water–9	3.37E+03	-	43
30	Cooling water pump F	Cooling water–1000	2.88E-03	-	20
31	Cooler E	H_4–17/ H_2–184/ N_2–850/ Water–9	-1.07E+02	-4.81E+01	177
32	Steam-turbine centrifugal compressor B	CH_4–375/ H_2–613/ Water–11/ N_2–2727/ NH_3–1266/ Ar–611	1.38E+03	-	147/38
33	Cooling water pump G	Cooling water–9816	2.83E-02	-	20
34	Cooler F	CH_4–375/ H_2–613/ Water–11/ N_2–2727/ NH_3–1266/ Ar–611	-1.05E+03	-2.62E+02	93
35	Refrigerator A	CH_4–375/ H_2–613/ Water–11/ N_2–2727/ NH_3–1266/ Ar–611	1.30E+03	-	25
36	NH_3 separator A	CH_4–375/ H_2–613/ Water–11/ N_2–2727/ NH_3–1266/ Ar–611	-	-	-23
37	Heat exchanger B	-	-	-	-
38	NH_3 converter	CH_4–375/ H_2–613/ N_2–2727/ NH_3–289/ Ar–611	1.53E+02	-	158
39	Heat recovery E	CH_4–375/ H_2–436/ N_2–1909/ NH_3–1283/ Ar–611	-1.41E+03	-8.45E+02	371
40	Refrigerator B	CH_4–17/ H_2–7/ N_2–32/ NH_3–18/ Ar–10.23	2.42E+01	-	38
41	NH_3 separator B	CH_4–17/ H_2–7/ N_2–32/ NH_3–18/ Ar–10.23	-	-	-23
42	Flue gas	CH_4–17/ H_2–7/ N_2–4/ NH_3–18/ Ar–10.23	-	-1.53E+03	
43	NH_3 storage tanker	NH_3–991/Water–9	-	-	-23

The ammonia manufacturing process may be divided into the following sub-processes:

A) **Synthesis gas preparation sub-process**
The synthesis gas is a mixture of hydrogen, nitrogen, and carbon oxides. The main goal of this process is preparing a synthesis gas of nitrogen and hydrogen in the stoichiometric ratio of 1 : 3.

The reaction in equation (1) occurs in steam reforming where hydrogen is formed from natural gas. Air is used as a nitrogen source. Oxygen is involved in an oxidation reaction in a secondary reformer. Carbon monoxide from a steam reforming is converted into carbon dioxide in a high/low temperature shift converter, which is illustrated by equation (2). Excess water is removed in a gas/liquid separation. The overall reaction is shown in equation (3). This sub-process is indicated by (A) sub-process in Fig. 1.

$$CH_4 + 0.7\ H_2O + 0.275\ O_2 \rightarrow 2.7\ H_2 + 0.75\ CO + 0.25\ CO_2 \quad (1)$$

$$0.75\ CO + 0.75\ H_2O \rightarrow 0.75\ CO_2 + 0.75\ H_2 \quad (2)$$

Overall reaction

$$CH_4 + 1.45\ H_2O + 0.275\ O_2 \rightarrow 3.45\ H_2 + CO_2 \quad (3)$$

B) **Carbon dioxide separation/purification sub-process**
The synthesis gas (substances in the right hand side of equation (3)) passes through an absorption tower to separate carbon dioxide. Hydrogen and nitrogen go to the ammonia synthesis sub-process. Carbon dioxide is desorbed for use in a carbon dioxide stripper process. The absorbent (methylethanolamine, MEA) is recycled to the absorption tower. This is indicated by the (B) sub-process in Fig. 1.

C) **Ammonia synthesis sub-process**
The remaining carbon oxides in the synthesis gas are removed through a methanation process. Then, the pure synthesis gas, which consists of hydrogen and nitrogen, is compressed in a steam-turbine centrifugal compressor and combined with the recycled gas. Ammonia is synthesized in an ammonia converter by the catalytic reaction of hydrogen with nitrogen. This reaction is illustrated in equation (4). The ammonia product stream is refrigerated, and then ammonia is separated by an ammonia separator. The ammonia synthesis sub-process is indicated by (C) in Fig. 1.

$$3H_2 + N_2 \rightarrow 2NH_3 \quad (4)$$

The raw material requirements and the process/fugitive emissions are estimated in **Table 2**. The ammonia manufacturing process has no process emission streams, except emissions associated with energy consumption and fugitive emissions. Energy-related emissions are not taken into account in Table 2 because the energy source varies from site to site. Emissions from burning flue gas are also excluded in Table 2. Those emissions should be subtracted by emissions from an avoided energy, which is equivalent to the energy recovery from the flue gas in order to take the benefit of energy recovery into account. Once the energy source is decided, those emissions are easily calculated by the emission factor of energy while considering the efficiency of the utilization of energy. Emissions shown in Table 2 are therefore fugitive emissions that are estimated by a rule-based calculation [12]. With the energy requirements and the emissions in the ammonia manufacturing process, the multi-output allocation procedure is explored in the next section.

Table 2: Raw material requirement and process emissions in 1,000 kg ammonia production process. (Does not include energy-related emissions) [12]

Raw material	
Substance	**Quantity [kg]**
Air	1,108
Natural gas	447
Water	1,200

Chemical process emissions to air	Quantity [kg]
Argon	3.05
CH_4	2.23
CO	2.9
CO_2	5.93
H_2	3.07
NH_3	6.42

2.2 Macroscopic approach

In the macroscopic approach, the unit process is the overall ammonia manufacturing process (A, B, and C). There is no subdivision of process. A unique allocation factor set is applied for the entire sub-processes regardless of function. The allocation factor may be a physical property or an economic property depending on a causal relationship chosen in a study.

2.3 Quasi-microscopic approach

The process in the ammonia manufacturing process can be subdivided into a joint sub-process and a separated sub-process depending on function. The joint sub-process is a process where two products/functions can not be technically separated, like the synthesis gas preparation sub-process (A). The separated sub-process is a process that delivers only one product/function, like the carbon dioxide separation/purification sub-process (B) or the ammonia synthesis sub-process (C).

Furthermore, the separated sub-process can be divided into two types, a fully separated sub-process and a physically separated sub-process. The fully separated sub-process is a process that can not affect other products/functions. For example, the ammonia synthesis sub-process is a fully separated sub-process because ammonia synthesis could occur with any source of nitrogen and hydrogen and thus is independent. The physically separated sub-process is a process that is physically separated, but influences the other products/functions. The physically separated sub-process in the ammonia manufacturing process is the carbon dioxide separation/purification sub-process. Carbon oxides are poisons to the ammonia synthesis catalyst. Suppose there is no carbon dioxide separation process in the ammonia manufac-

turing process. Though carbon dioxide can be removed in the methanation, the methanation process can not remove all of carbon dioxide because of the limitation of hydrogen concentration. Thus, the carbon dioxide separation/purification sub-process (B) is a physically separated process for any realistic manufacturing plant.

The unit process in the quasi-microscopic approach becomes each sub-process instead of the overall ammonia manufacturing process itself. There are therefore three unit processes in the ammonia manufacturing process (A, B, and C).

The allocation procedure in the fully separated sub-process is not needed. All of environmental loadings from the ammonia synthesis sub-process are allocated to ammonia. The environmental loadings in the joint sub-process and the physically separated sub-process are allocated to ammonia and carbon dioxide by a proper allocation factor set.

A simple allocation factor set is a physical/economic property ratio of the products, for example, ammonia and carbon dioxide in the ammonia manufacturing process. The same allocation factor set is applied to the joint sub-process and the physically separated sub-process. The allocation factor set therefore equals to the allocation factor set in the macroscopic approach. The fugitive emissions from a fully separated sub-process do not need the allocation procedure, while the fugitive emissions from a joint sub-process or a physically separated sub-process is allocated to the products by the same allocation factor set used in the joint sub-process and the physically separated sub-process.

2.4 Microscopic approach

The unit process in the microscopic approach becomes an operational engineering unit. The operational units are classified into a joint process, a fully separated process, and a physically separated process depending on function. However, because there are smaller processes, like a distillation column, the amount of energy or emissions that must be allocated are smaller. Hence, a more accurate allocation picture emerges. The type of process in the ammonia microscopic approach is represented in **Table 3**. As mentioned previously, the unit operations in the fully separated process do not need the allocation procedure. The environmental loadings associated with the unit operations in a joint process or a physically separated process are allocated to ammonia and carbon dioxide. The only difference for ammonia manufacturing from the quasi-microscopic approach is that the cooler B (19), the cooling water pump C (18) and the carbon dioxide storage tanker (20) become a fully separated process in the microscopic approach because those processes are related to carbon dioxide. These three operational units are used after the point in the overall process in which carbon dioxide is removed, and thus are allocated only to carbon dioxide. In the quasi-microscopic approach, the entire sub-process is subject to allocation rules. Working at the engineering unit process level, it is easier to identify processes that do not need allocation of any energy use or chemical emissions.

Since each unit operator in the joint process and the physically separated process is involved in producing both ammonia and carbon dioxide, it is very difficult to drive an allocation factor set based on causalities. For instance, in the primary reformer, natural gas is reacted with water to form hydrogen, carbon dioxide, and carbon monoxide. Hydrogen that is used in the synthesis of ammonia can not be formed without the formation of carbon dioxide and carbon monoxide. Therefore, the allocation factor set used in the quasi-microscopic approach is applied for all unit operators in the joint process and the physically separated process rather than estimating an individual allocation factor set for each operational unit. As can be seen, the microscopic approach allows the greatest flexibility in grouping processes so that allocation problems are reduced.

3 Results and Discussion

If a mass ratio of products is taken as an allocation factor, the allocation factor set, A1, becomes

$$A1 = \left[\frac{1000(\mathrm{kg\,NH_3})}{1179(\mathrm{kg\,CO_2})+1000(\mathrm{kg\,NH_3})}, \frac{1179(\mathrm{kg\,CO_2})}{1179(\mathrm{kg\,CO_2})+1000(\mathrm{kg\,NH_3})}\right] \quad (5)$$

The first element is for ammonia, and the second one for carbon dioxide. The allocation of fugitive emissions depends on the source of the emission. Comparisons between three approaches are shown in **Fig. 2** and 3 (→ *p. 226*) with the allocation factor set in equation (5). Fig. 2 shows the allocated value of energy requirement to ammonia and carbon dioxide. Fig. 3 shows the allocated values of the emissions. There are no differences in the allocated value of the raw materials between three approaches because the same allocation factor set is applied for each approach. The difference among the macroscopic approach, the quasi-microscopic approach, and the microscopic approach arises only in the energy requirement and the emissions, which are generally more influential in life cycle assessment. Though the

Table 3: Type of process in the microscopic approach for ammonia synthesis (→ Fig. 1)

Type of Process	Operational Unit
Jointed process	Compressor for air/ Pump A / Primary reformer / Cooling water pump A / Secondary reformer / Heat recovery A / High temperature shift converter / Heat recovery B / Low temperature shift converter / Heat recovery C / Cooling water pump B / Cooler A / Separator A
Physically separated process	CO_2 Absorber / Pump B / Heat exchanger A / CO_2 Stripper / Pump C / Cooling water pump D / Cooler C
Fully separated process	Cooler B/ Cooling water pump C / CO_2 Storage tanker / Heater / Methanator / Heat recovery D / Cooling water pump E / Cooler D / Steam-turbine centrifugal compressor A / Cooling water pump F / Cooler E / Steam-turbine centrifugal compressor B / Cooling water pump G / Cooler F / Refrigerator A / NH_3 separator A / Heat exchanger B / NH_3 converter / Heat recovery E / Refrigerator B / NH_3 separator B / NH_3 storage tanker

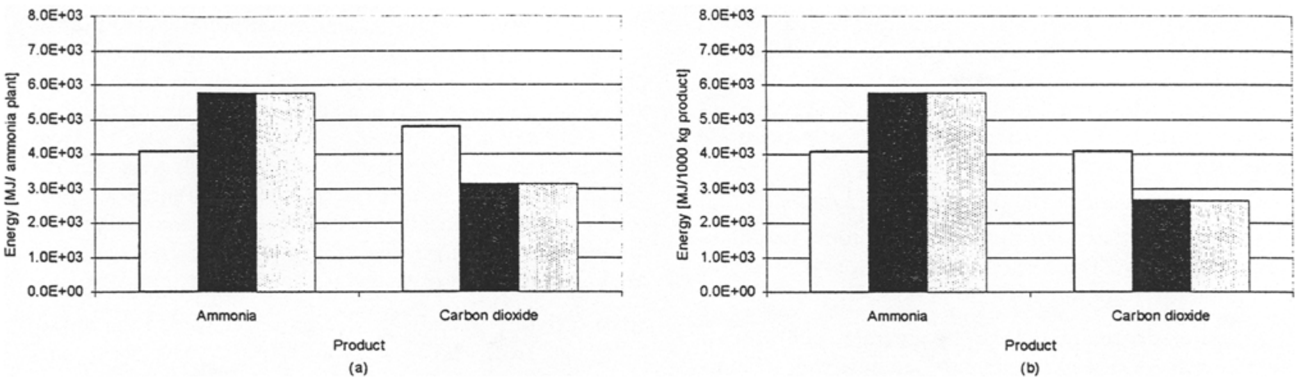

Fig. 2: Allocation in the energy requirement in the ammonia production process. (a) Ammonia manufacturing plant basis (b) 1,000 kg product basis. The blank bar represents the macroscopic approach. The black bar represents the quasi–microscopic approach. The dotted bar represents the microscopic approach.

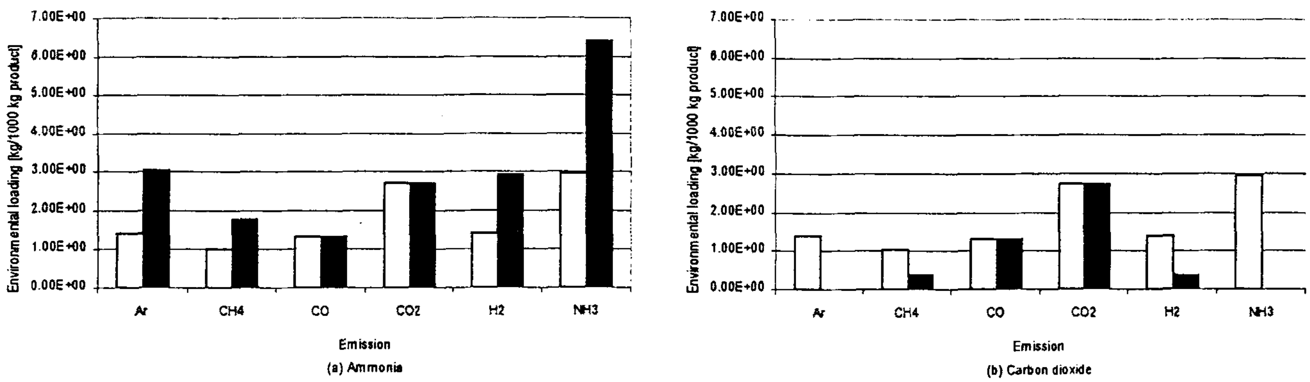

Fig. 3: Allocation in emissions in the ammonia production process. The blank bar represents the macroscopic approach. The black bar represents the quasi-microscopic and the microscopic approaches which in the case of ammonia are very similar.

classification of some operational units in the microscopic approach is different from that in the quasi-microscopic approach, results give almost the same value because in the case of ammonia the environmental loadings from those operational units are small.

As shown in Fig. 2-(a), which is based on the ammonia manufacturing plant, carbon dioxide in the macroscopic approach has more responsibility for the energy requirements in the ammonia manufacturing plant than ammonia because more carbon dioxide is produced than ammonia. The energy requirement in the fully separated sub-process, ammonia synthesis sub-process, is allocated to both carbon dioxide and ammonia. In the quasi-microscopic/microscopic approach, the energy requirement is more heavily allocated to ammonia than to carbon dioxide because the higher energy requirement in the ammonia synthesis sub-process is allocated to the ammonia. The energy requirements in the synthesis gas preparation sub-process and the carbon dioxide separation/purification sub-process are allocated to ammonia and carbon dioxide. Those cause the ammonia in the quasi-microscopic/microscopic approach to be allocated more energy to than the ammonia in the macroscopic approach.

Fig. 2-(b) shows the energy requirement based on 1,000 kg of each product. In the macroscopic approach, there is no difference in the energy requirement between ammonia and carbon dioxide. However, the quasi-microscopic/microscopic approaches show that ammonia requires more energy in manufacturing 1,000 kg of product than carbon dioxide because of the energy requirement in the ammonia synthesis sub-process. For energy, the less accurate macroscopic approach differed by as much as 40% from the more specific microscopic allocation. This illustrates the magnitude of allocation issues as developed in ISO 14041.

Regarding the fugitive emissions, ammonia and argon are not allocated to the carbon dioxide in the quasi-microscopic/microscopic approach because those chemicals are released only from the ammonia synthesis sub-process. Thus, the amount of ammonia and argon allocated to ammonia in the quasi-microscopic/microscopic approach is larger than in the macroscopic approach.

Fugitive emissions such as carbon dioxide and carbon monoxide in the quasi-microscopic/microscopic approach are allocated to both ammonia and carbon dioxide because those emissions are from the joint sub-process or the physically separated sub-process. Therefore, there are no differences between the quasi-microscopic/microscopic approach and the macroscopic approach. Methane and hydrogen are involved in both joint sub-process and fully separated sub-process. All of the fugitive emissions of methane and hydrogen from the fully separated sub-process are allocated to

ammonia in the quasi-microscopic/microscopic approach, and the fugitive emissions of methane and hydrogen from the joint sub-process are allocated to both ammonia and carbon dioxide. Ammonia in the quasi-microscopic/microscopic approach is thus allocated more methane and hydrogen to than in the macroscopic approach.

The macroscopic approach estimates some of the environmental loadings allocated to ammonia - energy, ammonia, argon, methane, and hydrogen, less than the quasi-microscopic/microscopic approach. This is due to the fact that with the macroscopic approach all of the environmental loadings from the fully separated sub-process are allocated to ammonia and carbon dioxide. In fact these emissions do evolve from the specific chemicals and thus are not adequately represented by the conventional allocation approach. For emissions, the magnitude of improvement toward more physically related allocation by using microscopic versus macroscopic is in the ranges of 50% - 100%. However, for some parameters, such as CO_2 and CO, there is little difference.

The quasi-microscopic/microscopic approach is very useful in identifying key pollution prevention issues within an overall process. Suppose that improving unit operations contributing more than 5% of total energy requirement is defined as a pollution prevention goal. A variety of processes could be examined but some priority is usually needed. The resulting key pollution prevention issues in three approaches are shown in **Table 4**. In the macroscopic approach, some operational units in the fully separated sub-process, ammonia synthesis sub-process are identified as a key pollution prevention issue for carbon dioxide. The function of those units is for the ammonia production and is not related to the carbon dioxide production. Key pollution prevention issue for the carbon dioxide production becomes an operational unit in the joint sub-process and the physically separated sub-process, not the fully separated sub-process.

As for ammonia as a product, there is a similarity between the macroscopic approach and the quasi-microscopic/microscopic approach except the refrigeration A process. In the macroscopic approach, refrigeration A process contributes 3.7% of the total energy requirement, while it is 5.8% of the total energy requirement in the quasi-microscopic/microscopic approach where the energy requirement in the ammonia synthesis sub-process is allocated to ammonia. Therefore, the quasi-microscopic/microscopic approach is helpful in better setting a priority among the improvement options. For CO_2 as a product (such as a supercritical solvent for polymer production), the quasi-microscopic/microscopic approach really sharpens the pollution prevention focus when compared to the macroscopic screening. The key pollution prevention issues shift to three processes in the microscopic approach instead of six in the macroscopic approach, Table 4. This illustrates clearly that the microscopic approach is very efficient in deciding the priority of the key pollution prevention issues.

4 Conclusions

It has been illustrated that the allocation results in a multi-output process are influenced significantly by defining the unit process, similar to the influence of an open loop recycling system where the allocation procedure depends on the system boundary. [13] This arises in a multi-input process as well. The unit process can be defined from the largest (an entire manufacturing process) to the smallest (an operational engineering unit), depending on the information constraints of a study.

There are three different alternatives in the multi-output allocation procedure, macroscopic approach, quasi-microscopic approach, and microscopic approach. Comparison among these three different approaches is shown in **Table 5**. In the macroscopic approach, the unit process becomes a

Table 4: Key pollution prevention issues in ammonia and carbon dioxide. (Those contributing more than 5% of total energy)

Ammonia		**Carbon dioxide**	
Macroscopic	Quasi–microscopic /Microscopic	Macroscopic	Quasi–microscopic /Microscopic
Compressor for air Heater A Steam turbine centrifugal compressor A CO_2 stripper Steam turbine centrifugal compressor B Primary reformer	Compressor for air Heater A Steam turbine centrifugal compressor A CO_2 stripper Steam turbine centrifugal compressor B Primary reformer Refrigeration A	Compressor for air Heater A Steam turbine centrifugal compressor B CO_2 stripper Steam turbine centrifugal compressor A Primary reformer	Compressor for air CO_2 stripper Primary reformer

Table 5: Trade-offs between three approaches. (+++) indicates better or larger

	Applicability		**Time/Cost**	**Identification of key issues /Process improvement**	**Unit process**
	Background	**Foreground**			
Macroscopic approach	+++	+++	+	+	Process
Quasi-microscopic approach	+	++	++	+++	Sub–process
Microscopic approach	+	++	+++	+++	Manufacturing operational unit

manufacturing plant. This approach is widely used in many LCA studies. It is easily applicable to both background system, such as electrical power generation system and foreground system, such as manufacturing plant under investigation. This approach requires less information on a process than the quasi-microscopic/microscopic approaches (→ *Table 5*).

In the quasi-microscopic/microscopic approach, a manufacturing plant is subdivided into two or three sub-processes and there may be a joint sub-process, a physically separated sub-process and/or a fully separated sub-process. The unit process becomes a sub-process in the quasi-microscopic approach, while it is an operational unit (such as a distillation column) in the microscopic approach. The quasi-microscopic/microscopic approach is very difficult for application to a background system because the background systems usually suffer from a lack of information. However, this can be solved if every industrial sector performs the allocation procedure by the quasi-microscopic/microscopic approach.

Though the quasi-microscopic/microscopic approach requires more information, it may not be very much more time or cost intensive. These improved allocation approaches can reduce the allocation procedure errors that might be based on a value judgement. Furthermore, if the multi-output process in a LCA study is in the foreground system, the microscopic approach is very useful in identifying key issues related with one product/function and improving the environmental performance of a process.

In the ammonia manufacturing process, the quasi-microscopic and the microscopic approaches give the same results. However, results from these two approaches can be different in other cases. A fully separated operational unit, which is in the physically separated sub-process can avoid the allocation procedure in the microscopic approach, but not in the quasi-microscopic approach. Therefore, the microscopic approach is recommended in the multi-output process due to the degree of the aggregation of operational units and the ability to minimize the number of the environmental burdens that must be allocated. As such, the microscopic approach would more clearly reflect the actual chemical product sources of energy needs or process chemical emission. The microscopic approach is also the obvious alternative in the rule-based LCI methodology as a full unit process accounting is provided. Thus, the microscopic approach facilitates the LCI of chemical and pharmaceutical products.

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News & Views: Guidelines for Implementation of Eco-indicator 99 with the Swiss ETH-database available

In 1999 the new method "Eco-indicator 99" for life cycle impact assessment has been introduced. The method has got much attention in the mean time. In order to use this method with existing LCI (life cycle inventory) databases it is necessary to assign the new damage factors to the resources and pollutants reported in these LCI databases. One of the widely distributed databases for background processes is the Swiss "Ökoinventare von Energiesystemen".

Our paper "**Eco-indicator 99 Implementation: Assignment of Damage Factors to the Swiss LCI database 'Ökoinventare von Energiesystemen'**" aims to link the new impact assessment method Eco-indicator 99 to the ETH-database in order to facilitate the usage and to avoid discrepancies due to misunderstandings or different interpretations of the original reports. The work consists of a short background paper and an Excel worksheet with all information about the prerequisites for the assignment. New Eco-indicator 99 scores have been extrapolated for some substances contributing to greenhouse effect, ozone depletion, acidification, ionising radiation and ecotoxicity. The damage factors from the Excel worksheet can be directly linked to results of the ETH-database.

The background paper and the Excel worksheet are available from ESU-services for 98 CHF. Please send your order with your full address to

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